COTTON GIN DUST EXPLOSIBILITY DETERMINATIONS

A Thesis

by

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ABSTRACT

Following the recent Imperial sugar dust explosion in 2008, a comprehensive survey of past dust explosions was conducted by the Occupational Safety and Health Administration (OSHA) to determine potential explosible dusts. After the survey, OSHA personnel listed dust found in cotton gins, or gin dust, fueled two explosions in the past. OSHA is required by law to regulate facilities handling explosible dusts to provide a safe working environment for employees. The dust handling facilities must test the dust for explosibility based on the American Society for Testing and Materials (ASTM) E 1226 to ensure proper regulation of facilities.

Dusts found in cotton gins were tested to determine if they are explosible. Safety Consulting Engineers Inc. (SCE) personnel tested gin dust in accordance with the ASTM method and reported that gin dust (GD) was an explosible dust. However, personnel from the Center for Agricultural Air Quality Engineering and Science (CAAQES) utilized the CAAQES test method and reported that gin dust was non-explosible. The goal of this research was to analyze the two different test methods and determine if gin dust should be regulated as an explosible dust. It is assumed that either the ASTM or CAAQES test method had incorrectly classified gin dust. The CAAQES test method was analyzed and tests were conducted on multiple dusts to the accuracy of the test procedure. A theoretical analysis of the ASTM test method was conducted to determine potential flaws in the test method.

The ASTM test method was found to be flawed. It used pressure as the only criterion for a dust explosion, utilized high energy ignition sources, limited the amount of oxygen, and had no requirement for a dust to have a minimum explosible concentration (MEC) to be classified as explosible. Utilizing high energy ignition source can result in a determination that a dust explosion occurred when the measured reaction was actually due to the ignition source and not a dust explosion. This type of test is referred to as an overdriven test. The CAAQES test method utilizes three criteria: a ruptured diaphragm, flame front leaving the chamber, and a characteristic pressure versus time curve to determine if a dust has a MEC. If a dust has a MEC, it is an explosible dust. By determining the MEC a more accurate classification of a dust can be made by utilizing the CAAQES test method, as CAAQES personnel did to determine that gin dust is not an explosible dust. An analysis of the ASTM and CAAQES explosible dust testing protocols was conducted to determine proper classification of gin dust.

Primary dust explosions occur in the process stream of facilities at locations where an explosible dust is entrained at concentrations above the MEC. A primary dust explosion may result in a series of secondary dust explosions. For a dust explosion to occur four criteria must be met simultaneously: there must be containment, a dust entrained in the air at or above the MEC, oxygen must be present, and there must be an ignition source. A theoretical analysis was conducted to determine if a MEC exists in a cotton gin. The results indicated that there were no locations in a cotton gin where a

MEC existed. It was concluded that gin dust is not an explosible dust and that dust explosions are not possible in cotton gins.

DEDICATION

This thesis is dedicated to my wife, Ashley N. Vanderlick, my parents, Walter G. and Ann V. Vanderlick, and my siblings, Jessica, Cecilia, and Felix, whose love and encouragement inspire me to be the best I can be.

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A very special thanks to Nick and Misty Taylor for reminding me how much fun work can be.

Finally, thanks to my mother and father for their encouragement and to my wife for her patience and love.

NOMENCLATURE

1.2-L	1.2 Liter Vertical Tube Apparatus
20-L	20 Liter Spherical Chamber Utilized in ASTM Testing
28.3-L	28.3 Liter Cubic Chamber Utilized in CAAQES Testing
ρ	Density
Δu	Change in Internal Energy
ΔT	Change in Temperature
η	Efficiency of Cyclone
μm	Micrometers
AED	Aerodynamic Equivalent Diameter
ASTM	American Society for Testing Materials
atm	Atmospheres
bph	Bales per Hour
C	Carbon
CAAQES	Center for Agricultural Air Quality Engineering and Science
cfm	Cubic Feet per Minute
CI	Confidence Interval
CO_2	Carbon Dioxide
Conc	Concentration
C_v	Specific Heat at Constant Volume
deg K	Degrees Kelvin

dP/dt	Rate of Pressure Rise
EF	Emission Factor
ft^3	Cubic Feet
g	Grams
$g_{\text{fine dust}} / m^3_{\text{air}}$	Grams of Fine Dust per Cubic Meter of Air
$g_{\text{conveyed}} / m^3_{\text{air}}$	Grams Conveyed per Cubic Meter of Air
$g_{\text{trash}} / m^3_{\text{air}}$	Grams of Trash per Cubic Meter of Air
GD	Gin Dust
GR	Ginning Rate in Bales per Hour
GSD	Geometric Standard Deviation
hr	Hour
J	Joule
K_{st}	Deflagration Index
kJ	Kilo Joules
L	Liters
lbs	Pounds
M_i	Mass Flow Rate
m^3	Cubic Meters
$mass_{\text{air}}$	Mass of Air
$mass_{\text{PM}}$	Mass of Particulate Matter
MEC	Minimum Explosive Concentration
min	Minutes

MFR	Mass Flow Rate
MMD	Mass Median Diameter
mol	Moles
MW	Molecular Weight
N_2	Nitrogen
NEP	National Emphasis Program
O_2	Oxygen
OSHA	Occupational Safety and Health Administration
P	Pressure
P_{ex}	Maximum Explosive Pressure
PM	Particulate Matter
PSD	Particle Size Distribution
R	Gas Constant
s	Seconds
SCE	Safety Consulting Engineers Inc.
T	Temperature
VRF	Variable Rate of Flow

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

The sugar dust explosion in Georgia on February 7, 2008 killed 14 workers and injured many others (OSHA, 2009). As a consequence of this dust explosion, the Occupational Health and Safety Administration (OSHA) revised its Explosible Dust National Emphasis Program (NEP). An explosible dust expert forum in May 2011 reported that facilities handling suspected explosible dusts must test their dusts and perform risk assessments of explosible dust hazards. If a dust is determined to be explosible, OSHA is required to regulate all facilities handling that dust to prevent dust explosions. To determine possible explosible dusts, OSHA conducted a comprehensive survey of reported dust explosions and fires in the past. Based on this survey, OSHA personnel reported that dust found in cotton gins may have caused dust explosions on two separate incidences. However, the reports that cotton gins had experienced dust explosions were not supported by documented investigations. There are significant differences between fires and dust explosions. Cotton gins periodically have fires, but these fires are not dust explosions. It is assumed that the two reported incidences were the result of fire marshals incorrectly labeled gin dust as fueling a dust explosion.

In the literature, a dust explosion is more accurately a "deflagration" in contrast to another type of explosion, a detonation. A deflagration differs greatly from a detonation and consists of a dust cloud being ignited with the resulting pressures causing significant damage. Typically, a primary deflagration is followed by multiple secondary deflagrations. In contrast, a detonation is initiated by a detonator that creates a pressure wave that serves as the igniter of the explosive. A detonation is fueled by materials such as dynamite or ammonium nitrate in contrast to the dust entrained in the air that serves as the fuel for a detonation. In a detonation, the flame speed and the pressure wave travel at a speed equal to or greater than the speed of sound (330 meters per second). In a deflagration, the pressure wave moves away from the source at a speed equal to or less than the speed of sound, while the flame front follows at approximately 1 to 10 meters per second (Palmer, 1973).

An explosible dust is a dust with a MEC. A MEC is the minimum concentration of dust entrained in air that will result in a self-propagating flame through the dust cloud. Palmer (1973) defines a Group ‘A’ explosible dust as one that propagates a flame in the test apparatus when ignited by a small energy source (10 J) in contrast to Group ‘B’ dusts which do not self-propagate a flame in the test apparatus. Palmer (1973) noted that not all dusts with volatiles are explosible. The only way to properly determine if a dust is explosible is to testing it for a MEC. If there is a concentration of a dust that results in a self-propagating flame through the dust cloud when ignited, the dust is explosible.

Dust explosions occur in series. The first explosion, referred to as the primary dust explosion, occurs in a small volume, such as the boot of a leg in a grain elevator. A pressure rise occurs when the dust is converted to gas as the flame self-propagates through the dust cloud. Primary dust explosions are relatively small, contrasting to a secondary dust explosion, with a maximum pressure of less than 0.1 bar gauge. The pressure ruptures the initial containment, resulting in a pressure wave and flame front moving into a larger secondary containment volume. Unburned dust in the primary explosion may also be conveyed by the pressure wave to the secondary volume and serve as fuel for a secondary deflagration (Lesikar et al., 1991). The fire front follows the pressure wave and, if there is a MEC, serves as the ignition source for the secondary explosion in the larger volume. Secondary dust explosions may result in maximum pressures of over 7 bar gauge (100 psi gauge) and cause extensive damage to facilities (Palmer, 1973; Parnell, 1980; Lesikar et al., 1991; Parnell, 1993). All dust explosions subsequent to the primary are referred to as secondary explosions, with multiple secondary explosions common in dust explosions events.

Deflagrations pose serious safety risks for grain handling facilities. Not only must facilities comply with numerous OSHA rules and standards designed to provide safe working conditions for employees, but the high occurrence of dust explosions demonstrates that the risk is still present. On October 29, 2011, a grain dust explosion in a Kansas grain elevator killed six and injured two more. In the ensuing OSHA investigation, the grain elevator was fined in excess of $400,000 dollars for twelve violations after not having been cited for any violations in the eight years leading up to the dust explosion (OSHA, 2013). The lack of OSHA violations prior to the deflagration illustrates the difficulty of preventing dust explosions in grain handling facilities as well as the limited effectiveness of OSHA regulations.

The concentrations of dust present in a facility can be determined by conducting an analysis of the process stream. Primary dust explosions can occur in locations that dust concentrations are at or above the MEC, such as grain transfer points in grain elevators. Palmer (1973) lists the MEC of cornstarch as 40 g/m^3, which is typical of many agricultural dusts. Preventing dust explosions in grain handling facilities can be achieved by engineering ventilation systems to reduce the concentrations at grain transfer points to less than the MECs (NFPA 68, 2007; NMAB 367-2, 1982; NMAB 367-3, 1982; NMAB 367-4, 1983).

As a consequence of the reported explosions in cotton gins from the survey, tests were conducted to determine if cotton gin dust (GD) was explosible. Explosibility tests were performed by CAAQES and SCE personnel. CAAQES and SCE personnel used different test methods to determine if GD was explosible. The results of the explosibility tests conducted by SCE were that GD was a Class 'A' explosible dust while the CAAQES test results determined that GD was non-explosible. The difference in results from SCE and CAAQES prompted a CAAQES study, and Parnell et al. (2012) reported that the ASTM test method used by SCE was flawed.

SCE conducted tests in an enclosed spherical 20-liter (L) chamber with pyrotechnic chemical igniters with 5 and 10 kJ of ignition energy. The only criterion used to indicate a deflagration in the 20-L chamber was pressure. If the pressure rise inside the 20-L chamber exceeded one bar gauge, then it was assumed that a deflagration had occurred. In contrast, the CAAQES testing system utilizes a 28.3-L cubic chamber with a stationary ignition source, a diaphragm and three different criteria to indicate a deflagration.

Cashdollar, K.L and K. Chatrathi (1992) describe a situation in laboratory testing when the igniter flame is too large relative to the volume of the chamber as an overdriven test. When overdriven, a test could appear to result in an explosion, while it is actually just dust burning in the igniter flame with no real propagation beyond the igniter. The ASTM response to overdriven results is to test the dust in a one cubic meter chamber.

In order for a deflagration to occur, the flame must self-propagate through the dust cloud. If a moving, 10,000 J igniter flame is forced through the dust cloud to the opposite side of the chamber, it is likely that the dust will be classified as explosible if any volatiles are present (Parnell et al., 2012). Parnell et al. (2012) illustrated that only 5.5 grams of oxygen are contained in the 20-L chamber and a stoichiometric combustion of 2 grams of dust will consume all the oxygen in the chamber. The tests performed by SCE personnel where they concluded that GD was explosible used a 10,000 J igniter flame forced through the chamber containing 20 grams or 1,000 g/m^3.

The CAAQES method utilized the following equipment and procedures: (1) testing the dust in a 28.3-L, cubic chamber with a diaphragm that bursts at approximately 0.1 bars; (2) a stationary coil ignition source; (3) a video camera used to capture the deflagration frame by frame; and (4) pressure recordings. Using this method, a dust was determined to be explosible if it had a MEC. The protocol required three replications of a concentration above the MEC and reducing the concentration until no explosion occurred. In the CAAQES method, the following three criteria were used for determining whether a deflagration had occurred: (1) the diaphragm was ruptured: (2) the flame front exited the chamber; and (3) a characteristic pressure versus time curve was obtained.

Objectives

To characterize GD and make a determination on the potential for dust explosions in a cotton gin, the following objectives were established:

1. Analyze the ASTM and CAAQES explosibility testing procedures and protocols.
2. Determine if a MEC can occur in a cotton gin.

CHAPTER II

ANALYZE THE ASTM AND CAAQES EXPLOSIBLE DUST TESTING PROTOCOLS*

Introduction

In December 2009, the National Cotton Ginners Association made a request to the CAAQES to conduct explosibility tests on dust found in cotton gins to determine whether it is explosible. In January 2010, the director of CAAQES reported that GD is not an explosible dust. However, in June 2010, SCE personnel reported that GD is explosible according to the ASTM testing method.

The dust characteristics that may affect the MEC include particle size, particle density, energy content and percent volatile material. However, the correlation between these characteristics and dust explosibility is not defined well enough to determine if a dust is explosible without testing a dust for its explosibility. The only way to determine if a dust is explosible is to test for a MEC. If there is a concentration of a dust at which a flame will self-propagate, then there is a MEC and the dust is classified as explosible.

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* Reprinted from Journal of Loss Prevention in the Process Industries, Vol. 26, Issue 3, C. B. Parnell, R. O. McGee, B. Ganesan, F. J. Vanderlick, S. E. Hughs, K. Green, A Critical Evaluation of Combustible/Explosible Dust Testing Methods – Part I, Pages 427-433, Copyright 2013, with permission from Elsevier

CAAQES personnel utilized the CAAQES method to test GD as described by Parnell et al. (2012). Dust explosion testing in accordance with the CAAQES test method requires the use of a 28.3-L (1ft^3) cubic chamber with a diaphragm and a stationary heated coil ignition source, as shown in figure 1. The chamber is constructed of Plexiglas© which allows for visual confirmation of a dust explosion and an accurate determination of the volume of the chamber occupied by the dust cloud, which affects the concentration of dust being tested. A pressure sensor is fitted in the chamber to record the change in pressure during each trial.

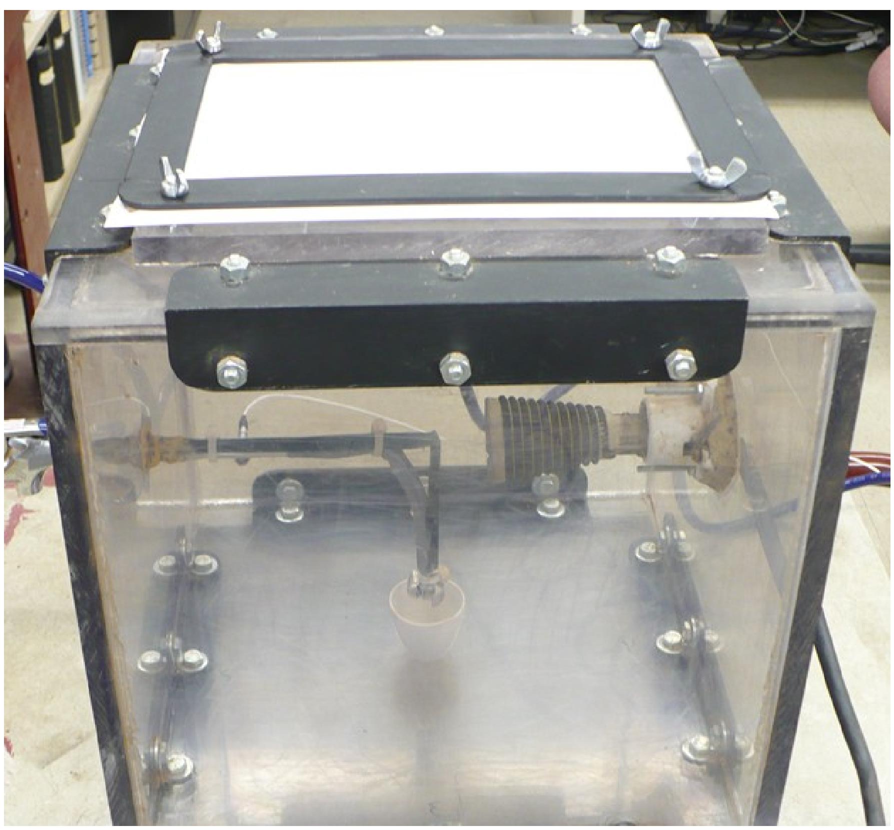

Figure 1. Front view of 28.3-L chamber used in CAAQES testing.

Using the CAAQES method, a dust is found to be an explosible dust if a MEC exists. In the CAAQAES method, a deflagration had occurred if the diaphragm ruptures, the flame front leaves the chamber, and a characteristic pressure versus time curve is obtained. Each test was recorded and the video was analyzed to determine if the flame front exited the chamber.

The pressure versus time curve for a deflagration of cornstarch at 56 g/m^3 is shown in figure 2. The pressure rises as the dust cloud was ignited by the stationary coil resulting in a self-propagating flame through the dust cloud. Sequentially, the diaphragm ruptured at approximately 0.1 bar gauge, releasing the pressure and flame front, creating a vacuum inside the chamber. Ambient air then entered the chamber, returning it to atmospheric pressure. A pressure versus time curve displaying these traits is referred to as a characteristic pressure versus time curve in the CAAQES test method.

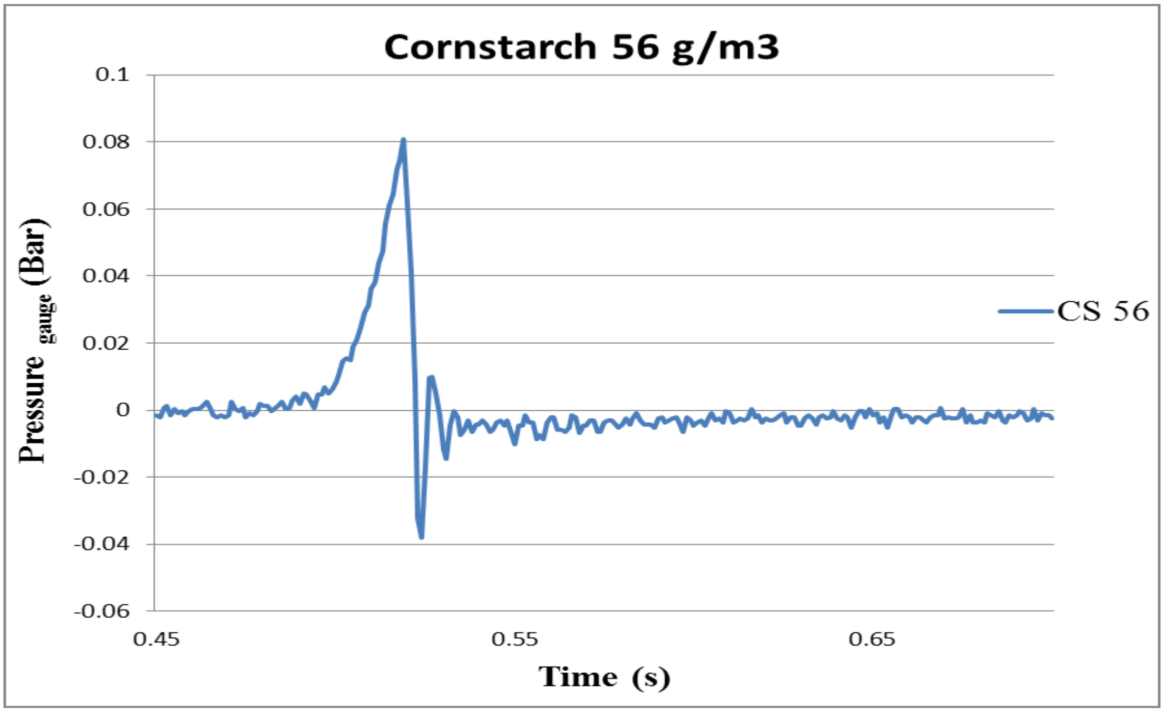

Figure 2. Characteristic pressure versus time curve obtained in CAAQES testing.

CAAQES personnel tested gin dust at concentrations ranging from 100 to 1,000 g/m^3 and no deflagrations were observed. The diaphragm remained intact, and the characteristic pressure versus time curve was not obtained in any of the 30 trials conducted, compelling CAAQES personnel to report that GD is not explosible to the National Cotton Ginners Association.

SCE tested GD utilizing the ASTM test method E1226-05 standard for testing explosible dusts. Dust explosion testing in accordance with the ASTM standards requires the use of a totally enclosed 20-L spherical metal chamber. 2.5, 5, or 10 kJ pyrotechnic igniters are fired through the dust cloud and across the chamber. It is assumed the dust cloud is uniformly distributed in the volume of the spherical chamber. Pressure rise is the only criterion used to determine if a deflagration occurred in the ASTM test method. If the pressure rise exceeds 1 bar, the dust is classified as explosible. Palmer (1973) used 10 J as the ignition energy for dust explosibility testing. The ASTM test method uses relatively high ignition energies of up to 10 kJ to ensure that sufficient energy is provided for proper classification of “hard to ignite” dusts. Any volatile material that is contacted by the moving chemical flame would combust, increasing the pressure inside the chamber without self-propagation of a flame. Cashdollar (2000) described the situation in which the combustion of volatiles in the chamber was due to the moving high energy ignition source, rather than the self-propagation of the flame, as an overdriven test.

ASTM E1226-05 is the Standard Test Method for Pressure and Rate of Pressure Rise for Combustible Dust, and it is the standard method used to determine the explosive characteristics of a dust, including the deflagration index (K_{st}), maximum explosive pressure (P_{ex}), and rate of pressure rise (dP/dt). The explosive characteristics of the dust are used to determine the preventive and control measures needed by facilities handling the dust, such as the design of explosion venting. Testing in accordance with ASTM standard E1226-05 relies only on pressure rise and does not require that the MEC of a dust be determined for explosive classification.

ASTM E1515-07 is the Standard Test method for Minimum Explosible Concentration of Combustible Dusts. Use of 2.5 or 5 kJ pyrotechnic igniters is recommended in the 20-L spherical chamber for MEC testing. Deflagration is defined in ASTM E1515-07 as a rise in pressure of 1 bar gauge over the pressure rise of the igniter.

However, a warning in E1515-07 states that if a dust ignites with a 5 kJ igniter but not with a 2.5 kJ igniter then the system may be overdriven.

Methodology

CAAQES Test Method

The particle size and ash analysis for GD was determined and compared with explosible dusts, cornstarch and dust XX. Dust XX is a manufactured dust, from an undisclosed source, that consists of clay surrounded by animal fat.

The ash analysis was conducted to determine the percent of non-volatile material in a dust sample. The protocol consisted of pre-weighing three samples of each dust and post-weighing following four hours in a furnace at 300 degrees Celsius (575º F). Increased fractions of inert dust will either increase the MEC or prevent the flame from propagating through the dust cloud (Palmer, 1973). The results of the ash analysis are shown in table 1. GD was found to have the highest ash content with 87 percent while only 13 percent of GD was combustible.

Table 1. Results of ash analysis performed on test dusts.

Dust Type	Ash% ± 95% CI
Cornstarch	0.98 ± 0.02
Dust XX	61.6 ± 0.01
Gin Dust	87.2 ± 1.13

The particle size distributions (PSD) were performed using the coulter counter Multisizer in the BAEN department at Texas A&M University and the results are shown in table 2. Dust samples typically have a lognormal distribution and are defined by mass median diameters (MMD) and geometric standard deviation (GSD) (Cooper and Alley, 2002).

Table 2. Results of particle size analysis performed on test dusts.

Dust Type	MMD ± 95% CI	GSD ± 95% CI
Cornstarch	15.5 ± 0.29	1.6 ± 0.08
Dust XX	13.7 ± 0.06	2.1 ± 0.03
Gin Dust	23.7 ± 0.88	1.9 ± 0.01

Explosible dust tests were conducted on cornstarch and Dust XX utilizing the CAAQES test method for a comparison to GD. Three trials were conducted at each concentration until no deflagrations occurred. The MEC for cornstarch was determined to be 43 g/m^3, which is similar to the 40 g/m^3 published by Palmer (1973), and at 43 g/m^3, one of the three trials, CS 43_3, resulted in a deflagration. The MEC for Dust XX was determined to be 73 g/m^3. The pressure versus time curves for cornstarch at 43 g/m^3 is shown in figure 3. A dust cloud of cornstarch at 43 g/m^3 contacting the stationary ignition source is shown in figure 4.Subsequently, the resulting diaphragm rupture and the flame front leaving the chamber, signifying a dust explosion occurred, is shown in figure 5.

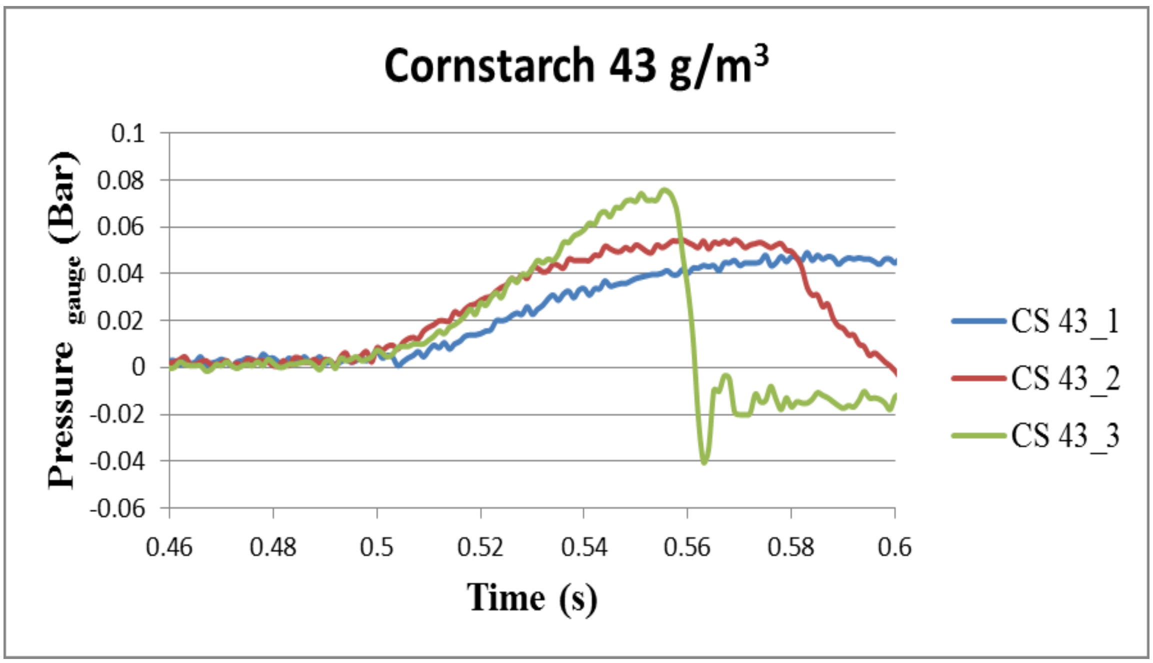

Figure 3. Pressure versus time graph for cornstarch at 43 g/m^3. Only one dust explosion was observed (CS 43_3).

Figure 4. Cornstarch at 43 g/m^3 contacting stationary ignition source.

Figure 5. Ruptured diaphragm and flame front leaving chamber, signifying a dust explosion for cornstarch at 43 g/m^3.

GD was tested at concentrations from 100 to 1,000 g/m^3, utilizing the CAAQES test method, with three trials conducted at each concentration and no dust explosions were detected. Flames were detected when the GD contacted the stationary ignition source. However, no self-propagation of a flame was observed. The diaphragm was not ruptured and no characteristic pressure versus time curve was obtained. The pressure versus time curve for GD at 1000 g/m^3, which is typical for all concentrations of GD, is shown in figure 6. The flat lines demonstrated that no dust explosions were observed in the CAAQES chamber.

A review of the video recordings taken of the tests of GD showed that no dust explosions occurred. GD igniting as it contacts the stationary ignition source is shown in figure 7 and the presence of the flame demonstrates that the energy of the igniter is greater than the ignition energy of gin dust. The flame continued to burn as GD contacted the stationary ignition source. However, no self-propagation of a flame was detected, as shown in figure 8.

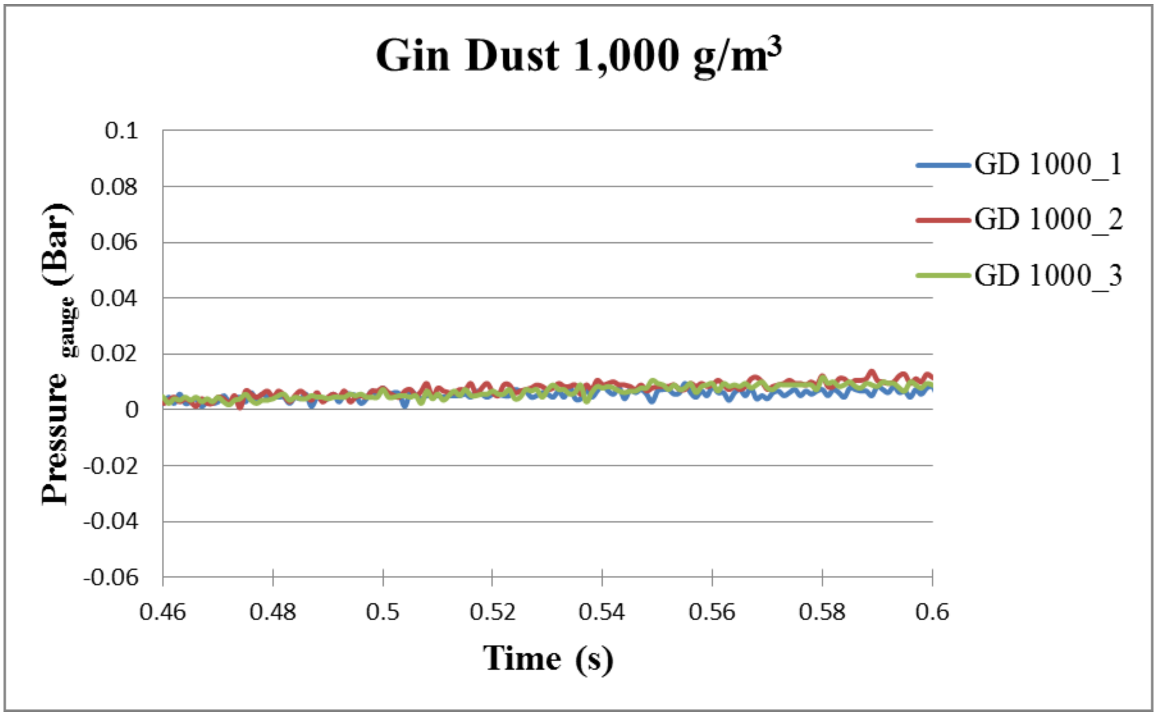

Figure 6. Pressure versus time curves for GD at 1,000 g/m^3. No dust explosions were detected.

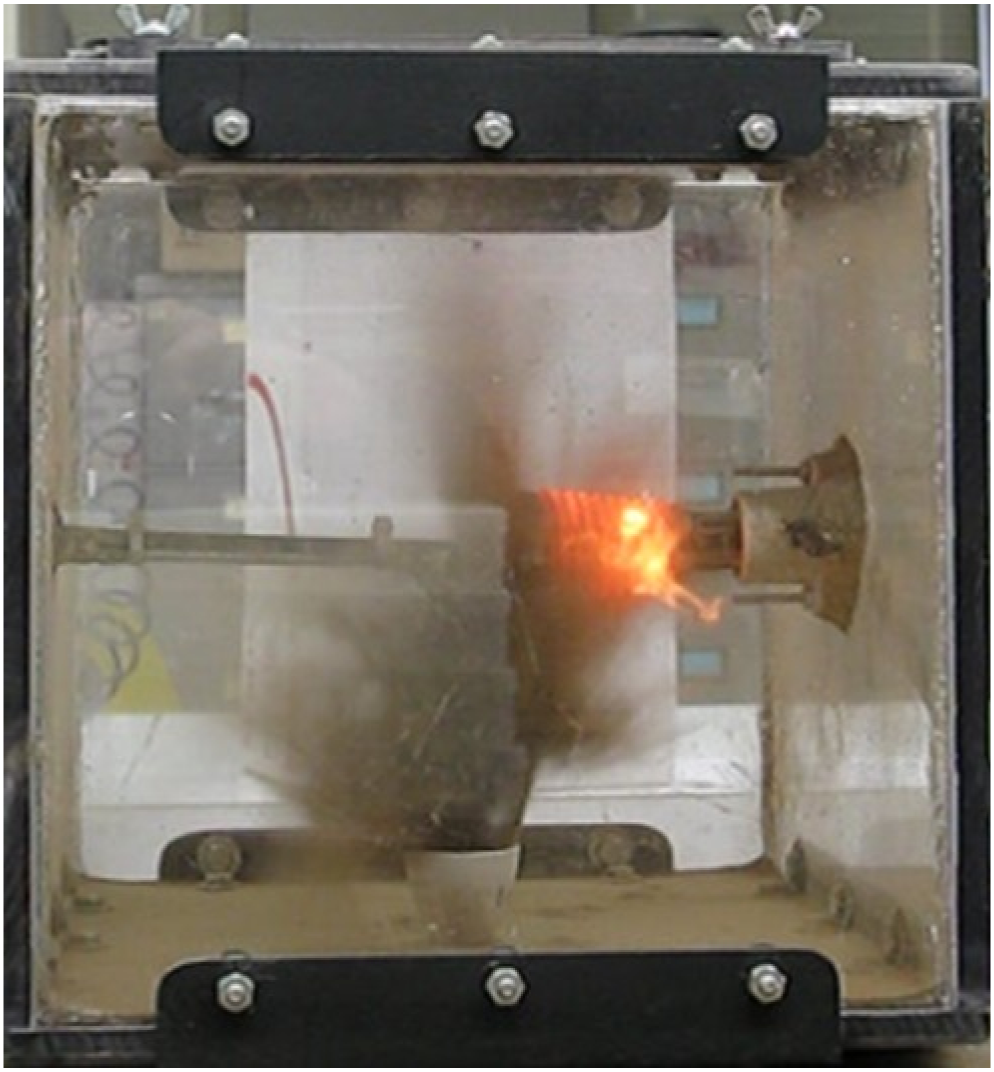

Figure 7. Gin dust at 1,000 g/m^3 igniting as it contacts the stationary ignition source.

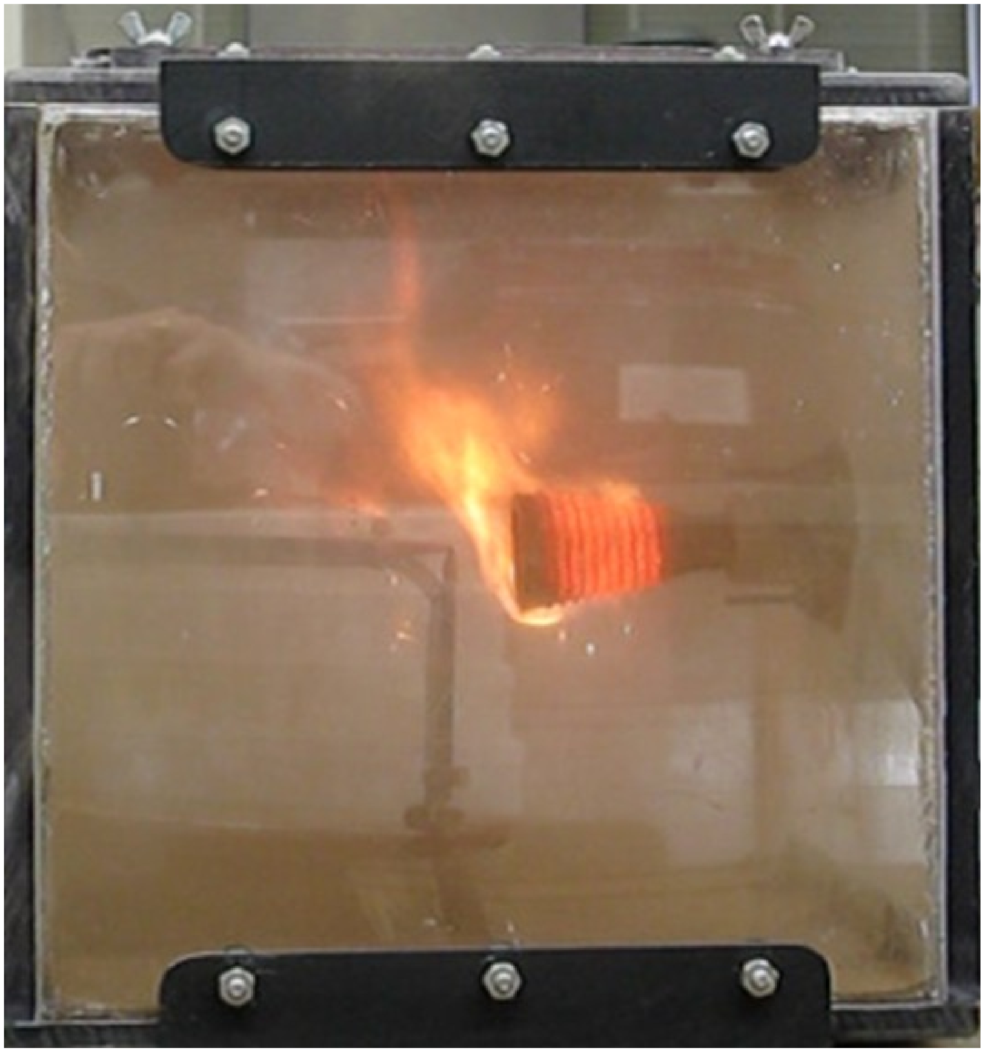

Figure 8. No self-propagation of flame from stationary ignition source for gin dust at 1,000 g/m^3. The intact diaphragm and lack of flame exiting the chamber demonstrates that a dust explosion did not occur.

ASTM Test Method

A portion of the sample of GD was sent to SCE to test it for explosibility based on the ASTM E1226-05 standard for explosible dust testing in spring 2010. SCE personnel conducted a screening test described by Bartknecht (1989) utilizing the 1.2-L

Vertical Tube Apparatus (SCE, 2010). The weighed sample was dispersed in the chamber with a blast of compressed air. A dust was classified as explosible if a flame was observed self-propagating away from the 10 J continuous arc ignition source.

Samples of gin dust from 0.25 to 20.0 grams (g) were tested with ten trials at each of the eleven different concentrations. It should be noted that 0.25 and 20.0 g is equivalent to approximately 210 and 17,000 g/m^3 respectfully, assuming uniform dispersion in a 1.2-L test chamber. No flame propagation was observed in the 110 trials conducted.

Since no flames were detected, SCE continued testing in a 20-L spherical chamber recommended by the ASTM standard. The dust was classified explosible if the maximum pressure was greater than or equal to 0.4 bar. SCE did not report why they used 0.4 bar as an explosion indicator. A 10 kJ ignition source was used to test GD at a concentration of 1,000 g/m^3, and reported a maximum pressure of 5.6 bars. SCE concluded that gin dust was a combustible dust and continued with testing the explosive characteristics using ASTM E1226-05. Gin dust was tested in 15 trials with concentrations ranging from 125 to 3000 g/m^3 with a 10 kJ ignition source. SCE reported the characteristics of gin dust as: P_{ex} of 5.5 bars, dP/dt of 97 bar/s and K_{st} of 26 m*bar/s.

Once GD was classified as class ‘A’ explosible by SCE, at the request from CAAQES personnel, SCE continued with MEC testing. SCE noted in their report that testing for MEC can be determined using ASTM E1515-07. From SCE’s description of the method used it appears that SCE used the ASTM E1515-07 method. The 20-L spherical chamber was used with a 5 kJ ignition source and an explosion pressure of 0.5 bars or greater was used to determine if a deflagration had occurred. SCE did not state how the 0.5 bars criterion was determined or why it differed from the 0.4 bars used in the explosibility classification test. Seven trials were conducted at concentrations ranging from 100 to 400 g/m^3. SCE reported the MEC for GD as 300-350 g/m^3.

Theoretical Analysis of 20-L Chamber

The pressure rise recorded in the ASTM tests can be approximated using a simple adiabatic reaction of carbon being consumed by a thermal reaction using the ideal gas law and the constant-volume sensible heat equation. The following simple reaction is hypothesized as the reaction of burning carbon representing the combustible dust in a 20-L chamber:

$$C + O_2 + 3.76N_2 \rightarrow CO_2 + 3.76N_2 \qquad (1)$$

where, C – Carbon (moles)

O_2 – Oxygen (moles)

N_2 – Nitrogen (moles)

CO_2 – Carbon dioxide (moles)

One mole of carbon (Molecular Weight (MW) =12) reacts with one mole of oxygen (MW=32) with the requisite 3.76 moles of nitrogen (MW=28) that accompanies the air. This thermal reaction produces one mole of CO_2 (MW 44). Equations 2 and 3 illustrate the calculations of molecular weight before and after the reaction. The molecular weight of the gas prior to the reaction consisting of one mole of oxygen and 3.76 moles of nitrogen at standard temperature and pressure is 28.8 grams per mole. The MW after the reaction consisting of one mole of carbon dioxide and 3.76 moles of nitrogen is 31.4 grams per mole.

$$MW_{before} = \frac{32 + 3.76 * 28}{4.76} = 28.8 \tag{2}$$

where, MW_{before} – Molecular Weight, before reaction (g/mole)

$$MW_{after} = \frac{44 + 3.76 * 28}{4.76} = 31.4 \tag{3}$$

where, MW_{after} – Molecular Weight, after reaction (g/mole)

Equation 4 is the equation for gas density derived from the ideal gas law. The density of the gases prior to the thermal reaction is 1.19 grams per liter. The density of gases after the reaction is a function of the temperature and pressure.

$$\rho = \frac{P*MW}{R*T} = \frac{1*29}{0.08206*(273+25)} = 1.19 \tag{4}$$

where, ρ – Density of Gasses (g/L)

P – Pressure (atm)

MW – Molecular Weight (g/mole)

R – Gas Constant (L*atm/deg K*moles)

T – Temperature (deg K)

The mass of air in a 20-L chamber is 23.8 g (1.19 g/L * 20L) prior to the reaction and 24.8 g after the reaction, assuming complete combustion of one gram of carbon. The 20-L chamber contains 5.5 g of O_2 and 18.3 g of N_2 prior to the reaction; after the reaction, the MW of the CO_2 and 3.76 moles of N_2 is 31.4 grams per mole. One gram of carbon (0.0833 moles) will consume 2.67 g of O_2 (0.0833 moles) in a stoichiometric reaction. For this scenario, the oxygen will be completely consumed by 2 g of carbon.

The specific heat at constant volume (C_v) is defined as the ratio of the change in internal energy (Δu) per unit mass required to increase gas temperature by one degree Kelvin (ΔT).

$$Cv = \frac{\Delta u}{\Delta T} \tag{5}$$

where, C_v – Specific Heat at Constant Volume (J/g*deg K)

Δu – Change in Internal Energy (J/g)

ΔT – Change in Temperature (deg K)

The C_v of the gases produced was used to determine the temperature rise. The weighted average of C_v was assumed to be 0.95 J/(g-deg K), based on the mass fraction of CO_2 and N_2 after the reaction.

The estimated internal energy content of one gram of combustible dust from an agricultural source is 16 kJ/g. SCE was required to test, according to the ASTM test method, at 1,000 g/m^3, with an ignition flame from a 10 kJ energy source before gin dust could be classified as non-explosible. The total energy in the chamber would be 26 kJ. The energy per unit mass (Δu) would be equal to 1050 Joules per gram or 26 kJ divided by 24.8 grams. The temperature rise, using equation 5, would be 1050/0.95=1100 degrees Kelvin, and the absolute temperature would be 1400 degrees Kelvin. Using the ideal gas law, the absolute pressure due to this rise in temperature would be 4.5 bars or a pressure rise of 3.5 bars gauge.

Results and Discussion

The three criteria utilized when testing in accordance with the CAAQES test method more accurately classify a dust as explosible over the ASTM method. The rupture of the diaphragm indicates that a pressure rise occurred. Video recordings can be utilized to show the flame self-propagated through the dust cloud and the flame front exiting the chamber. The characteristic pressure versus time curve allows the reaction in the chamber to be compared to a characteristic dust explosion, while the presence of a flame in the testing demonstrates that GD is not a “hard to ignite” dust. A dust sample must have a MEC for the dust to be classified as an explosible dust, when utilizing the CAAQES test method.

The results of calculating the theoretical pressure rise due to 2.5, 5 and 10 kJ ignition sources, assuming no heat is lost to the walls of the chamber, is shown in table 3. The resulting pressure rise due to 2.5, 5 and 10 kJ igniter in the 20-L chamber was 0.4, 0.7, and 1.4 bar gauge, respectfully. ASTM E1515-07 suggests the effects should be established for each size of igniter in order to correct for the difference in pressure rise due to the igniter. The calculated pressure rise from 1 gram of agricultural dust being combusted in the 20-L chamber is also shown in table 3. The pressure rise due to combustion of one gram of agricultural dust will result in a dust being classified as explosible when no flame self-propagation occurred.

Table 3. Theoretical pressure rise in a 20-L chamber due to different ignition energies.

Ignition Energy kJ	Dust Energy kJ	Temp (absolute) deg K	Pressure (absolute) Bar	Pressure (gauge) Bar
2.5	0	400	1.4	0.4
	16	1080	3.5	2.5
5.0	0	510	1.7	0.7
	16	1190	3.9	2.9
10	0	722	2.4	1.4
	16	1400	4.5	3.5

An energy content of 16 kJ per gram, similar to many organic dusts, was used for the calculations for table 3, while the energy of carbon is approximately 32 kJ per gram. The energy content of a dust is critical because the more energy that is released in the combustion reaction, the higher the temperature and pressure rise will be. The calculated pressure rise would be even greater if the energy content of the dust was 32 kJ instead of 16kJ.

The results shown in table 3 are the theoretical values from a combustion reaction, with no requirement for the flame to self-propagate through the dust cloud. The pressure rise due to combustion of dust can be determined by subtracting the pressure rise due to the igniter alone. The pressure rise due to combustion of 1 gram of agricultural dust in a 20-L chamber is approximately 2 bars gauge, independent of the size of igniter used. The criterion to determine if a dust is explosible in the ASTM method is a pressure rise of 1 bar gauge. Theoretical calculations show that combustion of 1 gram of agricultural dust in the 20-L chamber will result in a dust being classified as an explosible dust without a self-propagating flame. Forcing a flame through a dust cloud can result in a pressure rise above 1 bar gauge without a dust explosion occurring. Use of a high energy pyrotechnic chemical ignition sources may result in the combustion of the dust cloud without a self-propagating flame.

Several flaws have been identified with the ASTM test method. The use of pressure as the only criterion does not ensure a dust explosion occurred, and the effects of the igniter in a 20-L chamber with no dust present will produce a pressure rise of over 1 bar gauge, resulting in incorrect classification of a dust. The analysis of the procedures used by SCE revealed that values of 0.4 and 0.5 bars were being used as indicators to determine if a dust explosion had occurred. The change in the criterion by the testing laboratory demonstrates that the ASTM protocols are not clearly written and are being misinterpreted. The use of relatively high energy pyrotechnic energy sources does not ensure the flame self-propagates through the ASTM test chamber.

GD was tested for dust explosibility by SCE and CAAQES personnel. An ash content of 87 percent was an indicator that flame self-propagation would not occur (Palmer, 1973). SCE reported not flame self-propagation in the screening testing performed in the 1.2-L chamber, but still reported GD was an explosible dust. No flame self-propagation was detected in the CAAQES testing. A flame was detected on the stationary ignition source in CAAQES testing, demonstrating that the energy of the igniter was above the ignition energy of GD.

Conclusions

There are many flaws associated with the ASTM test method. The use of high ignition energy will result in an overdriven test. A dust must have a MEC to be an explosible dust. The use of pressure rise as the only criterion does not ensure a dust explosion occurred. Limited oxygen is available for reaction in the 20-L ASTM chamber. A non-explosible dust may be incorrectly classified as an explosible dust when utilizing the ASTM test method. The CAAQES test method mimics a primary dust explosion in facilities, such as grain elevators. The use of three criterion with the CAAQES test method ensure a dust explosion occurred. Utilizing the CAAQES test method, a more accurate dust explosibility classification can be made. Gin dust was determined to be non-explosible because no MEC exists.

CHAPTER III

A THEORETICAL ANALYSIS TO DETERMINE IF A MEC OCCURS IN A COTTON GIN

Introduction

Prevention of primary dust explosions in facilities will result in the prevention of all dust explosions. Primary dust explosions occur in contained areas of a process stream where a MEC of explosible dust is present. Cornstarch has a MEC of 40 g/m^3, which is typical of many agricultural dusts. The process stream of the facility handling the dust can be analyzed to determine locations at which MECs can occur. The process stream can be designed with control measures to prevent all the requirements of a dust explosion from occurring. The control measures will depend on the process stream and operating conditions. The concentration of dust can be reduced by ventilation or the addition of mineral oils to prevent a MEC from occurring (Parnell, 1993). Inert gasses can be used to reduce the amount of oxygen present. The potential ignition sources in this area can be reduced and preventive maintenance in these areas can be made a priority to reduce the probability of a dust explosion occurring.

To determine if MECs are present in cotton gins, the different stages of the ginning process must be analyzed. The gin receives seed cotton, which is composed of cotton lint, cotton seed and trash. The gin removes the trash as well as separates the lint from the seed. The process stream of a cotton gin can be approximated as an unloading system, first stage dryer/cleaner, second stage dryer/cleaner, gin stand, and the lint cleaner. A pneumatic conveying system is used to transport the cotton from one process to the next inside a cotton gin. It is assumed that if a MEC exists it will occur at a point in the pneumatic conveying system where the trash is separated from the lint and seed and at intersections of the process streams. For picked cotton, there is an average of 230 kg (500 lbs) of lint, 360 kg (800 lbs) of seed, and 90 kg (200 lbs) of trash per bale. This results in a mass of 680 kg (1,500 lbs) of seed cotton per bale entering the gin. A worst case scenario of stripped cotton being ginned through the same gin was also evaluated. For stripped cotton, the average amount of lint and seed is similar to picked cotton. However, stripped cotton can have as much as 454 kg (1,000 lbs) of trash per bale.

Methodology

A hypothetical gin operating at standard temperature and pressure was used to determine if a MEC occurs in a cotton gin. A cotton gin was approximated using values given by the Texas A&M Endowed Cotton Chair (Parnell, 2010). A flow rate of 1.9 cubic meters of air per kg (30 cubic feet of air per pound) of material was used as an estimate of the minimum volume-rate-of-flow (VRF) to convey the material through the pneumatic system of the cotton gin. As the seed cotton moves through the process streams, the mass of material is being reduced by the removal of trash and seed. Due to the removal process, the mass being conveyed will be reduced, resulting in a lower flow rate of material through the remainder of the process stream. It was assumed that the seed cotton entered the gin at 680 kg (1500 lbs) per bale (M_1) and the first stage dryer/cleaner removed 34 kg (75 lbs) of trash; therefore reducing the mass conveyed to the second stage dryer/cleaner to 646 kg (1425 lbs) per bale (M_2). The second stage dryer/cleaner was assumed to remove the same amount of trash as the first stage, reducing the total mass to 610 kg (1350 lbs) per bale (M_3) being conveyed to the gin stand. The gin stand separated the seed from the lint, resulting in 250 kg (550 lbs) per bale (M_4) being conveyed to the lint cleaner. The lint cleaner removes the remaining 23 kg (50 lbs) of trash per bale. It was assumed that same percentage of trash was removed by each part of the process stream in the worst case scenario.

The first examination will be of the pneumatic conveying system that transports the seed cotton through the ginning process. There are only negligible losses from the unloading process to the first stage of the dryer/cleaner, so the mass and flow rate of seed cotton through this portion of the process stream will be considered the same as the rate of seed cotton entering the gin. The air needed for any stage of the pneumatic conveying system (Q_i) for picked cotton can be calculated as shown in equation 6:

$$Q_i = GR_j * M_i * VRF * \frac{1}{60} \tag{6}$$

where, Q_i – Conveying Air Flow Rate (m^3/min)

GR_j – Ginning Rate (bales/hour), GR_1=20, GR_2=40, GR_3=60

M_i – mass of material in process stream (g/bale)

VRF – Volume-Rate-of-Flow (m^3/kg.), 1.9

For a ginning rate (GR) of 20 bales per hour (bph) the estimated air flow from the unloading system to the first stage dryer/cleaner, Q_1, was 420 cubic meters (15,000 cubic feet) per minute. The mass flow rate (MFR) of the seed cotton can be calculated as shown in equation 7.

$$MFR = GR_j * M_i * \frac{1}{60} \tag{7}$$

where, MFR – Mass Flow Rate (g/min)

GR_j – Ginning Rate (bales/hour), GR_1=20, GR_2=40, GR_3=60

M_i – mass of material in process stream (g/bale)

The MFR of the seed cotton from unloading to the first stage dryer/cleaner is estimated at 227,000 grams per minute, for a GR of 20 bales per hour. The MFR of cotton can be divided by the conveying air flow rate, as shown in equation 8, to result in the concentration of mass in the process stream. The result for the same part of the process stream results in a mass of 530 grams of cotton being conveyed per cubic meter of conveying air. Since the aerodynamic equivalent diameter (AED) for the seed and lint is much higher than 125 µm, most of the 530 g/m^3 is not capable of fueling a dust explosion (Parnell, 2010).

$$Conc = \frac{MFR}{Q_i} = EF * \frac{1}{1-\eta} * GR_j * \frac{1}{60} * \frac{1}{Q_i} \tag{8}$$

where, Conc – Concentration of mass conveyed to conveying mass (g/m^3)

MFR – Mass Flow Rate (g/min)

Q_i – Conveying Air Flow Rate (m^3/min)

EF – Allowable Emission Factor (grams/bale)

η – Efficiency of cyclone (decimal percent)

GR_j – Ginning Rate (bales/hour), GR_1=20, GR_2=40, GR_3=60

The ratio of trash in the process stream can be calculated by removing the 590 kg (1300 lbs) of seed and lint from the mass used in equation 7. There are approximately 71 grams of trash per cubic meter of conveying air from the unloading system to the first stage dryer/cleaner. However, tests conducted by Wang et al. (2004) determined that approximately only 5.5 percent of gin trash was fine dust. This results in the further reduction of the mass used in equation 7 to 0.055 times the 90 kg (200 lbs) of trash, resulting in a mass of 5 kg (11 lbs) per bale of fine dust in the conveying system from the unloading area to the first stage dryer/cleaner and a mass ratio of 4 grams of fine dust per cubic meter of conveying air. The remainder of the process stream was broken down as described above.

Results and Discussion

The concentrations for the different sections of the process stream were calculated as explained above using equations 6 and 7, and the results are shown in table 4. As seen in table 4, the highest mass ratio of fine dust to conveying air occurring in the pneumatic conveying system is approximately 4 g/m^3, not taking into account the presence of the particles larger than 125 µm that would act as inhibitors to a dust explosion. It should be noted that at no time did the concentration reach 40 g/m^3, which is the MEC for many agricultural dusts.

The concentrations for the worst case scenario were then calculated with the results shown in table 5. With 5 times the amount of trash present in the process stream the maximum concentration is 13 g/m^3. It would not be possible for a MEC to exist in a cotton gin even if the MEC of GD was 40g/m^3. However, the MEC of GD was determined to be much higher.

Table 4. Results for calculations of concentrations of GD in cotton gins.

Process Stream	Gin Size bph	Flow Rate of Air (Q_i) m^3/min	Concentration of Total Mass Conveyed g/m^3	Concentration of Trash g/m^3	Concentration of GD g/m^3
Unloading System to 1st Stage Dryer/Cleaner	20	420	530	71	4
	40	850	530	71	4
	60	1,300	530	71	4
1^{st} Stage Dryer/Cleaner to 2^{nd} Stage Dryer/Cleaner	20	400	530	47	3
	40	800	530	47	3
	60	1,200	530	47	3
2^{nd} Stage Dryer/Cleaner to Gin Stand	20	380	534	20	1
	40	760	534	20	1
	60	1140	534	20	1
Gin Stand to Lint Cleaner	20	150	534	49	3
	40	300	534	49	3
	60	450	534	49	3

Table 5. Results for calculations of worst case scenario of concentrations of GD in cotton gins.

Process Stream	Gin Size bph	Concentration of GD g/m^3
Unloading System to 1st Stage Dryer/Cleaner	20	13
	40	13
	60	13
1st Stage Dryer/Cleaner to 2nd Stage Dryer/Cleaner	20	10
	40	10
	60	10
2nd Stage Dryer/Cleaner to Gin Stand	20	5
	40	5
	60	5
Gin Stand to Lint Cleaner	20	10
	40	10
	60	10

Since the large particles act as inhibitors to a dust explosion, the abatement system, which is used to remove the fine dust from the air stream, was analyzed. The total emission factor (EF) for a cotton gin ginning picker cotton is 0.66 kg (1.4 lbs) per bale (EPA, 1995). Using a conservative cyclone efficiency of 90 percent, there would be 6,600 g (14 lbs) per bale of particulate matter (PM) being transported from the pneumatic conveying system to the cyclones (Parnell, 2010). Using equation 8, the mass of PM being conveyed through the system per mass of conveying air was calculated and is shown in table 6 for a ginning rate of 20, 40, and 60 bph.

The air velocity calculated for the unloading to first stage dryer/cleaner was used in the calculation of the concentrations being transported to the cyclones.

Table 6. GD concentrations in abatement system of cotton gin.

Gin Size bph	Concentration of GD g/m^3
20	5
40	5
60	5

The concentration does not change with a change in the ginning rate as expected because the increase in PM brought into the gin is offset by the increased amount of air needed to convey it. The increased mass being conveyed in the worst case scenario results in more conveying air being used in the abatement system, resulting in a decrease in the concentrations of GD in the abatement system. The concentration in the abatement system for all three sizes of gins in the worst case scenario was 5 g/m^3.

Conclusions

The presence of larger particles in the process stream of cotton gins would act as inhibitors to a dust explosion. Testing was conducted on GD at concentrations up to 1,000 g/m^3 by CAAQES personnel with no MEC being determined. The concentrations of GD found in a gin are less than 5 g/m^3, therefore it is not possible for a dust explosion to occur in the pneumatic conveying system of a cotton gin.

CHAPTER IV

SUMMARY AND CONCLUSIONS

Summary

Recent dust explosions have demonstrated the importance of regulating explosible dusts to prevent dust explosions. In a comprehensive review of dust explosions, GD was identified as a suspect explosible dust. Testing was conducted utilizing the ASTM and CAAQES test methods. SCE personnel, utilizing the ASTM test method, reported GD was an explosible dust. However, personnel from the CAAQES laboratory utilized the CAAQES test method and reported that GD was a non-explosible dust. An analysis of the ASTM and CAAQES test methods was conducted to determine why utilizing the two test methods resulted in different classifications of GD. An explosible dust determination for GD was made. An analysis of the process stream in a cotton gin was also conducted to determine the locations in a cotton gin where a MEC may occur.

Objective 1

Several flaws were identified with the ASTM test method. The use of pressure as the only criterion, in a 20-L chamber, does not ensure a dust explosion has occurred. A pressure rise of over 1 bar gauge is possible due to the igniter alone. SCE used a different ignition criterion than described in the ASTM protocols to determine if a dust explosion occurred, which suggests that the ASTM protocols are not clearly written or are being misinterpreted. It is assumed that the use of high energy igniters in testing GD in accordance with the ASTM test method resulted in an overdriven test.

The analysis revealed that the three criterion utilized with CAAQES testing require a dust explosion to occur in order to classify a dust as an explosible dust. The presence of a flame in testing GD is evidence that GD is not a “hard to ignite” dust. The lack of flame self-propagation in tests up to 1,000 g/m^3 utilizing the CAAQES test method as well as tests up to 17,000 g/m^3 utilizing the 1.2-L vertical tube apparatus by SCE was used to determine that no concentration of GD will result in a dust explosion.

Objective 2

The concentrations of GD in the process stream of a cotton gin were calculated to determine if it is possible for a MEC to occur. The use of air to convey material through the process stream reduces the concentrations of GD. The highest concentrations of GD in the process stream were found between the unloading system and the first stage dryer/cleaner. Analyzing gin sizes from 20, 40 and 60 bales per hour revealed that gin size does not affect the concentrations of GD due to the proportional increase of air used to convey the material through the process stream. The presence of larger particles in the process stream would act as inhibitors of flame self-propagation. The abatement system used to remove GD from the process stream was also analyzed for each of the three gin sizes. As expected the size of the gin did not affect the concentrations of GD found in the abatement system. The highest concentration of GD calculated for any location in the cotton gin was 5 g/m^3.

Conclusions

Objective 1

- Gin dust is a non- explosible dust because it does not have an MEC. Gin dust should not be classified as an explosible dust.
- OSHA should not regulate cotton gins for handling an explosible dust.
- There are many flaws associated with the ASTM test method. The use of high energy ignition sources and pressure as the only criterion for a dust explosion can result in non-explosible dusts being classified as explosible dusts. There is a potential for a test to be overdriven when utilizing the ASTM test method. The ASTM test methods are not clearly written and may be misinterpreted.

Objective 2

- A MEC cannot occur in a cotton gin. The highest calculated concentration for GD in the process stream of a cotton gin was 5 g/m^3.
- The concentration of dust found in the process stream of a cotton gin is independent of the size of the cotton gin.

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APPENDIX

Tables

Table 7. Results for CAAQES testing of Cornstarch.

Sample	Concentration (g/m^3)	Sample Size (g)	Deflagration? (Y/N)
CS 135_1	135	0.40	Y
CS 135_2	135	0.40	Y
CS 135_3	135	0.40	Y
CS 100_1	100	0.30	Y
CS 100_2	100	0.30	Y
CS 100_3	100	0.30	Y
CS 77_1	77	0.23	Y
CS 77_2	77	0.23	Y
CS 77_3	77	0.23	Y
CS 57_1	57	0.17	Y
CS 57_2	58	0.17	Y
CS 57_3	57	0.17	Y
CS 43_1	43	0.13	N
CS 43_2	43	0.13	N
CS 43_3	43	0.13	Y
CS 40_1	40	0.12	N
CS 40_2	40	0.12	N
CS 40_3	40	0.12	N
CS 37_1	37	0.11	N
CS 37_2	37	0.11	N
CS 37_3	37	0.11	N
CS 33_1	33	0.10	N
CS 33_2	33	0.10	N
CS 33_3	33	0.10	N

Table 8. Results for CAAQES testing of Gin Dust.

Sample	Concentration (g/m^3)	Sample Size (g)	Deflagration? (Y/N)
GD 730_1	730	2.20	N
GD 730_2	730	2.20	N
GD 730_3	730	2.20	N
GD 660_1	660	1.98	N
GD 660_2	660	1.98	N
GD 660_3	660	1.98	N
GD 585_1	585	1.76	N
GD 585_2	585	1.76	N
GD 585_3	585	1.76	N
GD 515_1	515	1.54	N
GD 515_2	515	1.54	N
GD 515_3	515	1.54	N
GD 440_1	440	1.32	N
GD 440_2	440	1.32	N
GD 440_3	440	1.32	N
GD 370_1	370	1.10	N
GD 370_2	370	1.10	N
GD 370_3	370	1.10	N
GD 295_1	295	0.88	N
GD 295_2	295	0.88	N
GD 295_3	295	0.88	N
GD 220_1	220	0.66	N
GD 220_2	220	0.66	N
GD 220_3	220	0.66	N
GD 150_1	150	0.44	N
GD 150_2	150	0.44	N
GD 150_3	150	0.44	N
GD 73_1	73	0.22	N
GD 73_2	73	0.22	N
GD 73_3	73	0.22	N

Table 9. Results for CAAQES testing of Dust XX.

Sample	Concentration (g/m^3)	Sample Size (g)	Deflagration? (Y/N)
XX 93_1	93	0.28	Y
XX 93_2	93	0.28	Y
XX 93_3	93	0.28	Y
XX 77_1	77	0.23	N
XX 77_2	77	0.23	Y
XX 77_3	77	0.23	Y
XX 73_1	73	0.22	N
XX 73_2	73	0.22	Y
XX 73_3	73	0.22	N
XX 70_1	70	0.21	N
XX 70_2	70	0.21	N
XX 70_3	70	0.21	N
XX 67_1	67	0.20	N
XX 67_2	67	0.20	N
XX 67_3	67	0.20	N